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The early impact of large wood introduction on the morphology and sediment characteristics of a lowland river

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ABSTRACT

1. This paper investigates the response of a reach of an overwidened, low gradient lowland river (the River Bure, UK), to the introduction of large wood as a restoration tool.
2. The dimensions and number of wood pieces were recorded in 12 jams initiated by wood emplacement in 2008 and 2010 in two separate sub-reaches. Geomorphological mapping of the entire reach illustrated the spatial distribution of features in and around the 12 jams and in a section of study reach that was free of wood. Aggregates of replicate sediment samples were obtained from 5 recurring patches / landforms surrounding each of the 12 wood jams. Two of the patch types were wood-related (within jams and on sediments accumulated at the bank toe adjacent to wood jams) and three represented the broader river environment (bare (unvegetated) river bed surface, bank face, floodplain surface). The sediment samples were analysed to establish their particle size, organic content and plant propagule abundance.
3. The wood jams partially spanned the river channel and contained large pieces of wood that created a more open structure than naturally-formed wood jams.
4. Major changes in channel morphology have occurred since wood emplacement. Where no wood was introduced, the channel remains wide and the gravel bed is buried by a layer of sand and finer sediment, probably delivered from surrounding agricultural land. In the restored reaches, fine sediment has accumulated in and around the wood jams, enhancing flow velocities in the narrowed channel sufficiently to mobilise fine sediment and expose the gravel bed. Channel narrowing has been enhanced by vegetation colonisation and stabilisation of the retained fine sediment
5. Sediment analysis reveals a progressive sediment fining with time since wood emplacement in 2008 and 2010, largely achieved within the two wood-related patch types. In addition, fine sediment retained around the emplaced wood shows a relatively higher plant propagule content than other patch types, suitable for sustaining plant succession as the vegetated side bars aggrade to bank level with channel narrowing.
6. Although channel narrowing and morphological adjustment has occurred surprisingly rapidly in this low energy, over-widened reach within the first few years following wood introduction, sustaining the recovery in the longer term depends on continued

delivery of wood by ensuring a natural supply of sufficiently large wood pieces from riparian trees both upstream and within the reach.

Keywords: Large wood; River restoration; Sediment properties; Lowland river

1. INTRODUCTION

Rivers worldwide are subject to anthropogenic influences that degrade habitat conditions and threaten biodiversity (Malmqvist and Rundle, 2002). Widespread among these impacts are a variety of physical alterations, including straightening, embanking, widening, and dredging, and the removal of large wood. These actions homogenize the geomorphological and hydraulic features of the channel and degrade river ecosystems, reducing their capacity to recover to a fully functioning state that is important for river and floodplain morphology and ecology (Hobbs and Norton, 2006; Palmer *et al.*, 2010).

Since the 1980s, there have been increasing efforts to actively restore the form and ecological function of degraded rivers (e.g. Roper *et al.*, 1997; Harrison *et al.*, 2004; Lepori *et al.*, 2005; Palmer *et al.*, 2010). Key techniques that have been used include the introduction of amore sinuous planform, soft engineering of river banks, introduction of boulders and planting schemes, the construction of artificial riffles and pools, and the installation of protective fencing material (see Roni *et al.*, 2008; RRC, 2013). More recently, large wood has been introduced river systems as a restoration tool (Palmer *et al.*, 2010; RRC, 2013).

The presence of large wood in relatively unimpacted river systems is known to be important for increasing hydraulic complexity and, as a consequence, mobilising, retaining, and sorting sediments. These processes result in morphologically complex river channels containing many distinctive wood-related landforms that support the life cycles of a variety of plants, insects and fish (e.g. Abbe and Montgomery, 1996; Gregory et al., 2003). The inferred importance of wood for fluvial geomorphology and aquatic organisms has also led to experimental and field research on the benefits of large wood introduction and the disadvantages of large wood removal for fluvial ecosystems (e.g. Riley and Fausch, 1995; Sundbaum and Naesland, 1998; Abbe *et al.*, 2003; Kail *et al.*, 2007; Lester and Boulton, 2008).

This paper presents some preliminary findings from research being undertaken on a reach of a single-thread, lowland river, the River Bure, Norfolk, UK, where felled trees have been introduced into the river channel as a restoration tool. This paper investigates the early response of a river to wood emplacement in 2008 and 2010 following sampling in May 2012. This paper addresses the following questions:

1. What are the characteristics of the wood jams at this early stage following their emplacement?
2. What are the morphological responses to wood emplacement?
3. What are the characteristics of sediments retained within patches / landforms directly associated with the introduced wood in comparison with other patch types within the study reach?

2. STUDY SITE

This study was conducted along a reach of the River Bure Norfolk, UK (Figure 1). The 240 m study reach (Figure 1B) is located on the Blickling Hall estate, near Aylsham (Grid Ref TG161301). The river is bordered by farmland, parkland and relatively open, mixed deciduous woodland. Riparian trees growing along the river margin are dominated by alder (*Alnus glutinosa (L.) Gaertn*).

The study reach has an average slope of 0.005 $m.m^{-1}$ and the active channel extends to an average width of approximately 7.6 m. The river banks are composed mainly of sand, silt and clay with occasional gravel lenses, whereas the bed material is gravel which is mainly overlain by a layer of finer sediment, predominantly sand and silt). The layer of sand and finer sediment on the river bed results from a combination of sediment delivery to the channel from the floodplain, particularly from cultivated land and historical widening of the channel which has led to a reduction in flow velocities (RRC, 2013).

Flow records from the River Bure at Ingworth (TG1921429614), which is the nearest gauging station to the study site, shows a mean annual discharge of 3.2 m3 s−1. The hydrological regime of the river is characterised by low summer flows with winter high flows averaging less than double the summer flows (Figure 2). Winter flows and floods (average discharge 4.3 m^3 s^{-1}) occur between January and March from heavy rains, sometimes superimposed on snowmelt runoff, while summer flows (average discharge 2.4 m^3 s^{-1}) occur between July and September (Whitehead, 2006). The varying water levels associated with the river's flow regime during winter and spring disturb sediments and vegetation within the active channel leading to widespread erosion of bars and also deposition of sediment.

Large wood had previously been removed from the reach to improve access for angling and to mitigate against flood risk. Following concerns raised by the local angling club regarding habitat quality for wild trout, and a desire to improve the conservation value of the reach, the National Trust site manager designed and implemented a river restoration scheme involving reintroduction of large wood (whole trees and logs; see RRC (2013) for full details). The wood was reintroduced into the study reach in two phases: within sub-reach R1 in autumn 2008, and sub-reach R2 in autumn 2010 (Figure 1B). Data presented in this paper were collected in May 2012, allowing examination of sediment properties and propagule abundance four and two years following restoration of sub-reaches R1 and R2, respectively. The large size of the wood pieces, their orientation, and the fact that artificial anchoring was rarely used gives them a semi-natural appearance and potentially natural function, providing an opportunity to observe early channel adjustments induced by the introduction of large wood.

3. METHODS

3.1 Experimental design

The study focused on 12 wood jams within the 240 m study reach, five in the 100 m long sub-reach R1, and seven in the 80 m long sub-reach R2 (Figure 3Ai). Three types of data were collected: (i) the geomorphological characteristics of the river channel were mapped for the entire study reach; (ii) the position and characteristics of all large wood pieces and jams were recorded; (iii) sediment samples were obtained and subsequently analysed for their particle size, organic matter and plant propagule content.

3.2 Channel morphology

The geomorphological characteristics of the study reach were mapped under low flow conditions. The survey focused on the active river channel and mapped the location and extent of channel bed features (e.g. pools and bars), substrate types (gravel, sand, finesediment (silt + clay)), large wood and vegetated areas. Dominant plant species in vegetated areas were identified. Since morphological adjustment depends on a combination of direct human modifications and fluvial processes, flow records from the River Bure at Ingworth were inspected to identify the timing of high flows between phases of wood introduction and post-restoration survey/sampling.

3.3 Large wood characteristics

The position of introduced wood pieces was recorded in April 2010 (following the second phase of restoration) by surveying the end points of each felled tree using a Leica TPS800 total station. The properties (Table 1) of all large wood pieces and jams that spanned at least 30 % of the channel width were surveyed between 9 and 11 May 2012. No significant changes in the position of the introduced large wood pieces had occurred in the intervening period. The outer dimensions (length, width and depth) of each wood jam were measured. The number and dimensions (length and diameter) of large wood pieces (> 10 cm in mid-diameter and > 1 m in length) within each jam were measured, from which the average length and width of the wood pieces were estimated. Some large wood pieces were inaccessible at the time of survey, but it was possible to obtain accurate dimensions for 38 out of the 74 large wood pieces that were counted. All measurements were made to the nearest 5 cm for lengths and 1 cm for diameters using a 30 m measuring tape and a 1 m rigid rule. The volumes of wood pieces were estimated from their length and diameter. Jam volumes were initially estimated from their outer length, width and depth, which was then multiplied by 0.2 to approximate the volume of wood rather than a combination of wood and air (Gurnell *et al.*, 2000).

3.4 Sediment sampling

Samples of sediment were collected in the two sub-reaches R1 and R2 during May 2012, following the recession of high winter flows using a stratified random sampling design. The sampling period preceded the main summer flowering period for the majority of species and so only captured the persistent seed bank (Thompson *et al.*, 1997).

Samples were collected from five patch / landform types (Figure 3Aii): bare (unvegetated) river bed surfaces (EB), sediment accumulated within wood jams (JM), the toe of banks immediately adjacent to wood jams (JB), the toe of bare eroding banks located away from wood jams (BK) and the top of the banks / floodplain surfaces close to the river channel (FP). These represented recurring patch types including two that were wood-related (JM and JB) and three that were not associated with wood jams (EB, BK, FP).

Sediment samples were collected using a 5 cm deep, 6 cm diameter cylindrical corer, to extract samples to a 5 cm depth as is typical for seed bank studies (Thompson *et al.*, 1997). Three well-spaced replicates were obtained from four of the patch types (JM, JB, BK, FP). For the final patch type (EB) four replicates were extracted to ensure that a sufficient volume of the < 4 mm fraction was obtained from the river bed, where samples might include gravel particles. The replicate samples were combined into one aggregate sample for each of the 5 patch types associated with the area around each of the 12 jams indicated in Figure 3. To avoid contamination, sampling proceeded in an upstream direction.

3.5 Sediment analysis

In the laboratory, the 60 aggregate samples were weighed, mixed and sieved through a 4 mm sieve to remove the coarser material. The volume and weight of the two fractions (> 4 and < 4 mm) were measured and then sub-samples of the finer fraction were extracted for particle size and organic content analysis, and for plant propagule analysis.

Sub-samples of 100 ml were extracted for particle size and organic content analysis. Each sample was weighed, dried for 48 hours at 55°C, desiccated and re-weighed, combusted for 5 hours at 550°C, desiccated again and reweighed. These measurements supported determination of the organic matter as a proportion of the dry weight (%Organic matter) by the loss-on-ignition method. The remaining mineral sediment sample was sieved (2 mm and 1 mm meshes) and a 5g sub-sample of the < 1 mm fraction was analysed by laser sizer to determine the particle size distribution. The resulting data (including the estimate of the > 4 mm fraction) allowed the gravel (%Gravel), sand (%Sand), silt (%Silt) and clay (%Clay) proportions of the dry weight to be determined as well as the median particle size (D_{50} in phi units) to be determined. With respect to the latter, note that the phi scale is a negative logarithmic scale, whereby low values indicate large particles and vice versa.

250 ml samples were extracted to estimate the abundance of viable propagules in each through germination trials. Since the aim of the propagule analysis was to investigate the relative abundance of propagules in different patch types rather than a full ecological analysis of species abundance, samples were stored and processed to ensure equal treatment and rapid processing of the samples. The samples were placed in cold storage (below 0°C) and were then processed at the same time over a period of 12 weeks using the seedling emergence method (Thompson *et al.*, 1997). The 250 ml samples were spread on 500 ml sterilised compost (FertileFibre®) in 20.5 x 15 x 5 cm plastic seed trays with 50 ml of vermiculite sprinkled on top. Seed trays were watered daily and illuminated for 16 h in every 24 h using 600-W Metal-Halide lamps. As propagules germinated they were counted, identified to species level and removed from the seed tray. When identification was problematic, seedlings were transplanted into pots and grown-on until their species, or at least their genus, could be determined. The number of germinated propagules per unit surface area of the original bulk sample (Propagule abundance) was then estimated. It is important to note that more samples and sampling times are needed to provide a robust assessment of the seed bank (e.g. Gurnell et al., 2008), and complex and time-consuming sample treatments are needed to maximise the number of species that germinate (e.g. Boedjelte *et al.*, 2002, 2003). Rather, the above methodology aimed at an efficient laboratory effort sufficient to support comparison of the relative abundance of the persistent seed bank and its main species.

3.6 Data analysis

Descriptive statistics were used to explore whether any trends were apparent in the field and laboratory data. Since many of the variables were not normally distributed and showed different variance within patch types and sub-reaches (wood introduction periods), non-parametric statistical methods were adopted. Kruskal-Wallis (KW) tests or Mann Whitney (MW) tests were used, as appropriate, to explore whether there were statistically significant differences in sediment variables among patch types (n = 12 aggregate sediment samples for each patch type) and sub-reaches (n = 5 sediment samples for R1 and n = 7 sediment samples for R2). Where KW tests indicated a significant difference ($p<0.05$) in a particular variable among patch types, multiple pairwise comparisons were performed using Dunn's procedure (Bonferroni corrected significance level) to identify which patch types showed significant differences in the assessed variable. Principal Components Analysis (PCA) was also used to explore multivariate associations within the sediment and propagule data set. KW and MW tests and PCA were performed using XLSTAT-Pro software (version 9.1.3, 2009).

4. RESULTS

4.1. Hydrological records

Flow data recorded from the River Bure at Ingworth showed ten periods of relatively higher flows (i.e. peaks over threshold (POT)) above the mean annual discharge between November 2008 and October 2010, when the first phase of wood restoration was under-taken in R1, and also showed six periods of relatively higher flows between November 2010 (when the second phase of wood restoration was undertaken in R2) and May 2012 (when post-restoration survey/sampling was undertaken) (Fig. 2). To access the importance of short-term geomorphological–hydraulic interactions, an analysis of the annual maximum series derived from the 1959–2012 daily flow record for the study site was undertaken, which revealed a mean annual maxima flood of 5.85 m^3s^{-1}. The hydrological data between the first phase of restoration and the time of survey/sampling indicated that the highest POT flow of 6.87 m^3s^{-1} occurred on 1 March 2010. The flow value has an annual exceedance probability of 0.5 and a return period of approximately 2 years, suggesting that it was sufficient to have driven some channel adjustment following the restoration.

4.2 Characteristics of wood jams and in-channel active channel features and patches

A total of 74 large wood pieces and trees of the species *Alnus glutinosa* were found incorporated into 12 wood jams along the River Bure study reach, and accurate measurements were obtained for 38 of these. The number of wood pieces in a jam ranged from 2 to 21, with a median of five pieces. Figure 4A shows that the length of wood pieces within jams varied greatly. The median length and diameter of the measured wood pieces were 9.91 m and 0.22 m, respectively, but wood piece sizes were highly variable and wood piece volumes ranged from 0.007 m^3 to 8.26 m^3 (median 0.32 m^3).

All wood jams except Jam 8 partially spanned the river channel, occupying approximately 45 % of the bankfull width (Figure 3Ai). Jam 8 was a high jam that spanned the channel. This had entered the channel naturally but was left in place in line with the restoration efforts. The median jam length, width and depth were 15.34 m, 2.87 m and 0.62 m respectively, but jam length and width varied greatly (Figure 4C and D). The mean estimated wood volume of jams for the 0.18 ha study reach, expressed as cubic metres per hectare of active channel area, was 10.08 m^3ha^{-1} but the volume and area of jams ranged, respectively, from 0.95 m^3 to 15.13 m^3 (median 3.48 m^3) and 14.16 m^2 to 71.20 m^2 (median 24.97 m^2).

The two sub-reaches showed some different wood characteristics. The median number of pieces incorporated into the jams was five in both subreaches but individual pieces were larger on average in sub-reach R1 (median length 11.61 m; median diameter 0.23 m) compared to sub-reach R2 (median piece length 8.32 m, median diameter 0.19 m). However, sub-reach R2 contained more wood pieces in total (49 compared to 25 in sub-reach R1), creating a higher volume of wood over a smaller area in the second phase of wood reintroduction (sub-reach R2 = 5.88 m^3ha^{-1}) compared to that of the first phase of wood reintroduction (sub-reach R1 = 4.20 m^3ha^{-1}).

Areas of vegetation colonisation and also of different bed sediment calibre were found within the study reach, particularly in the vicinity of the 12 wood jams (Figure 3B). The most frequently occurring bed features were pools and bars (mostly composed of sand underlain with gravel) which were usually located in close proximity to wood jams. Three calibres of substrate were identified (gravel, sand, and silt + clay (fine sediment)) with fine sediment mainly observed within jams and sand being the dominant substrate type along the reach. The vegetated areas were dominated by *Sparganium erectum* L., *Epilobium Hirstutum* L. and *Phalaris arundinacea* L., which were retaining and stabilising fine sediment along the channel margins to create vegetated bars at the bank toe in proximity to jams. Where jams and aggrading vegetated areas concentrated flow, the exposed channel bed was lowered and in some cases the underlying gravel bed was exposed (Figure 5). The central part of the study reach, which had not been subject to wood reintroduction and where there were no wood jams, showed few active channel features (a few small pools and bars) and little variation in substrate type (a near uniform sand bed) (Figure 3B).

4.3 Sediment and propagule characteristics

MW tests revealed statistically significant differences ($p<0.05$) in sediment characteristics between wood reintroduction periods, with R2 samples being coarser (significantly higher %Gravel) than R1 samples (Table 2). Figure 6A-F and Table 2 indicate that this is strongly influenced by the two wood-related patch types (JM and JB) which are significantly finer (higher D_{50}, higher %Silt and %Clay) for the longer-established wood jams (R1) compared to the more recently introduced jams (R2) (MW $p<0.05$). No other patch types show significant differences between the wood reintroduction periods. Sediment characteristics show high variability within most of the patch types, but Figure 6 indicates some differences between patches. The EB samples are significantly coarser (lower D_{50}, higher %Sand, lower %Silt and %Clay) with significantly lower organic matter content than the other patch types (KW $p<0.05$; Table 2). BK and FP samples are the most variable across most of the sediment properties, and JM and JB samples are associated with finer sediments (lower D_{50} and greater %Silt and %Clay) and intermediate / high organic matter content, although these differences are not statistically significant (Table 2).

The germination trials yielded one woody species (*Alnus glutinosa*), six herbaceous species (*Callitriche hamulata sens.str.* Kuetz. ex Koch, *Callitriche stagnalis sens.str.* Scop., *Urtica dioica* L., *Conyza sp*., *Hypericum humifusum* L. and *Plantago major* L.) and one graminoid species (*Agrostis spp*.). The 8 species identified indicate that the propagule bank along the River Bure is relatively species poor. On average, R1 samples contained more propagules than R2 samples (mean 281 propagules/m^2 compared to 233 propagules/m^2), although MW tests revealed that this difference was not statistically significant (Table 2). Figure 6G suggests a tendency for a greater abundance of propagules in R1 samples compared to R2 samples across the in-channel patch types (i.e. all except FP), although this difference is only statistically significant for the EB patch type (Table 2). Nonetheless, for R2 samples, FP patches contained statistically significantly more propagules than BK and EB patch types, with wood-related patch types (JM, JB) retaining intermediate amounts of propagules (KW $p<0.05$; Table 2). Overall, propagule abundance increases from the relatively propagule-poor EB and BK samples (mean 30.65 propagules/m^2 and 31.79 propagules/m^2) to JM (mean 186.49 propagules/m^2) through to FP (mean 496.97 propagules/m^2) and JB (mean 518.69 propagules/m^2) patch types (Figure 6G), with FP and JB samples containing significantly more propagules than BK and EB samples (Table 2).

4.4 Relationships between sediment characteristics and propagule abundance

Principal Components Analysis (PCA) was used to identify gradients in the sediment and propagule characteristics across the 60 samples (12 for each patch type). Because some of the variables were percentages and were not normally distributed, PCA was performed on a rank correlation matrix and the results are presented in Table 3. In this analysis %Silt and %Clay were combined because they were very highly correlated ($r = 0.99$, $p<0.0001$) and so they each provided almost identical information. The first principal component (PC1) explained over 68

% of the variance in the data set and described a gradient of increasing sediment organic matter (high positive loadings on %Organic matter) and sediment fining (high negative loadings on %Gravel and %Sand and high positive loadings on D_{50} and %Silt+%Clay). Although the second principal component (PC2) has an eigenvalue that is slightly less than 1, it was retained because it explained over 16 % of the variance in the data set and had one very strong positive loading on Propagule abundance. Therefore PC2 described a gradient of increasing propagule abundance.

Figure 7 plots the scores of the 60 samples on PC1 and PC2, and codes them according to wood reintroduction periods (Figure 7A) and patch type (Figure 7B) and Table 3 presents the results of MW and KW tests performed on the PC scores for these three groupings. Figure 7A shows considerable overlap in PC scores for the two wood reintroduction periods, and MW tests confirm no statistically significant differences between the R1 and R2 (Table 3). However, when PC scores for each patch type are compared across the two reintroduction periods (Table 3), KW tests show that PC1 scores for two wood-related patches (JM and JB) are significantly higher for R1 compared to R2, indicating sediment fining with time since restoration as noted above for Figure 7B. While there is overlap in PC scores among patch types on Figure 7B, some trends are evident. In particular, the in-channel non-wood related habitats BK and EB show variable scores on PC1 (variable particle size and organic matter content) but are consistently associated with low PC2 scores (low propagule abundance), while the wood-related patches (JM and JB) show high scores on PC1 (finer and more organic-rich sediments) and variable propagule abundances, and the FP samples are associated with finer, organic-rich sediments and high propagule abundances, plotting primarily in the upper right quadrant of the bi-plot in Figure 7B. KW tests followed by multiple pairwise comparisons of scores on PC1 and PC2 according to patch type show that JM, FP, JB and BK samples contain significantly finer sediment and more organic matter than EB samples, while FP samples contained more propagules than BK samples especially for R2 (Table 3).

5. DISCUSSION

This paper has reported on a river reach where wood emplacement has been adopted as a restoration tool. Our analyses provide a basis for addressing the three research question stated earlier and assessing the success of the restoration in relation to (i) the quantity of wood emplaced / retained in comparison with wood loadings in river channels of similar size (when scaled to wood size) but where wood retention reflects more natural processes; (ii) the morphological complexity of the wood emplacement reaches in comparison with the intervening reach where no wood has been emplaced; (iii) the processes underlying the apparent impacts of wood emplacement that can be inferred from the properties of sediments sampled in five recurring patch types.

Compared to published data of natural wood loadings in river reaches bordered by deciduous woodland (Gurnell, 2013), the individual wood pieces in the study reach are relatively large but the quantity of wood stored (mean wood volume of 10.08 m^3ha^{-1}) is relatively low. In addition to the relatively small number of wood pieces, virtually all jams along the study reach only partially span the river channel, making them rather open structures with a smaller hydraulic effect than jams found in rivers of similar size (when scaled to the size of the large wood pieces) but where wood jams have formed more naturally (e.g. Gregory and Davis, 1992; Gregory *et al.*, 1993; May and Gresswell, 2003).

Geomorphological mapping of the study reach allows comparison of the two sub-reaches where wood has been reintroduced with the intervening sub-reach which has not received wood. It is apparent that the sub-reaches with wood are morphologically more complex. Not only do they contain wood, but pools, vegetated and unvegetated bars, and areas where sand and finer sediment has been mobilised to expose the underlying gravel bed, are almost entirely confined to the two sub-reaches where wood has been introduced. The direct association between wood emplacement and the development of these features can be seen by comparing photographs of the same location at the time of wood emplacement and during the present research (e.g. Figure 6).

Evidence from the analysis of sediment samples from different patch types helps us to infer the processes operating to achieve the transformation that has so far been achieved in the river channel's morphology. The relatively finer sediments associated with the sub-reach that was restored first (in 2008) suggests a process of continuing fine sediment retention, which appears to be mainly associated with the two wood-related patch types (JM and JB). This suggests a process of progressive fine sediment retention within and around the introduced wood, which is supported by the fact that these patch types (JM and JB) are associated with the most consistently fine sediments in comparison with the other types, including the floodplain (FP) across all samples analysed. Vegetation colonisation, stabilisation and trapping of the fine sediment that has accumulated around the wood jams may also contribute to the trajectory of sediment fining, and has resulted in the emergence of vegetated bar features at the bank toe that were not present at the time of wood emplacement (e.g. Figure 6). Since plant propagules are most abundant in the samples taken from these areas (JB samples), an association can be inferred between fine sediment and propagule trapping, that not only explains initial vegetation colonisation of the retained sediment but contributes to vegetation succession as the bar aggrades and environmental conditions for plant germination and growth change (e.g. Gurnell, 2014). The coupling of finer sediment, organic material and propagules in the jam bank (JB) as well as the floodplain (FP) samples is well illustrated by the coded PCA plot in Figure 7B and confirms associations between the calibre, organic content and propagule abundance observed in sediment samples taken from different patches of the river bed of other rivers (e.g. Gurnell et al., 2007; Osei et al., 2015)).

The complex hydraulic effects of wood jams have been shown to induce scouring, deposition and sorting of sediment (Gomi *et al.*, 2004; Oswald and Wohl, 2008). In the over-widened study reach, these processes have resulted in the early stages of channel narrowing through the development and aggradation of vegetated side bars at the bank toe, which have concentrated flows into a narrower channel cross section. This narrowing appears to be associated with further retention of fine sediment in the vegetated channel margins as the lateral bars aggrade to floodplain level, and with mobilisation of fine sediment to expose the river's gravel bed within the central narrowing area of the channel. These processes of narrowing and deepening may eventually allow high enough flow velocities to move fine sediment effectively through the study reach. However, at the present time, the widespread burial of the river's gravel bed by sand and finer sediments, and the lack of significant pool, riffle and bar development within the exposed gravel patches, suggests that channel narrowing and the presence of wood have not yet achieved their full morphological effect. Rivers subject to a more natural wood supply tend to be characterised by a larger range and better-developed geomorphological features than those observed in the study reach (e.g. Collins et al., 2012, Gurnell, 2013, Wohl, 2013), indicating that the impact of the restoration is at an early stage and, given the low gradient, low energy, low wood supply and overwidened state of the River Bure, may take some time to fully develop. However, the enhanced supply of fine sediment from human activities on the floodplain, is helping to accelerate the process by providing the material for vegetated landform building and channel narrowing. Further physical adjustment can be anticipated in the longer term and following greater magnitude events. Longer term monitoring (minimum of 10 years) as recommended by Downs and Kondolf (2002) is essential to develop an understanding of longer term geomorphological–hydrological relationships and channel dynamics within a reach following restoration.

Channel morphological complexity induced by large wood within natural river systems has been shown to promote faunal diversity (e.g. Lockaby et al., 2002; Johnson et al., 2003; Steel et al.,2003; Entrekin et al., 2009; Wyzga et al., 2009). Even though the restored reach of the River Bure has not achieved structural heterogeneity similar to that of natural river systems, wood-related landforms such as exposed gravel patches and vegetated lateral bars may have inferred importance for faunal communities such as fish and macroinvertebrate (e.g. Crispin et al., 1993; Lester and Boulton, 2008; Nagayama et al., 2008). Gravel patches along the restored reach may serve as spawning sites for fish such as wild trout, while vegetated lateral bars along the channel margin mayp rovide shelter and food for a range of fish and invertebrate species. Therefore, large wood may be a resource of restoration and recovery value for attaining a balance between the ecology and geomorphology of degraded rivers.

6. **CONCLUSIONS**

The introduction of large wood as a restoration tool provides important physical structures that enhances hydraulic diversity within the restored reach. Complex flow patterns drive mineral sediment, organic matter and plant propagule mobilisation, deposition and sorting, allowing discrete sediment patches and landforms with different properties to develop. Even in the low gradient, low energy, overwidened river reach investigated in this paper, the introduction of large wood has had major impacts on channel morphology within a few years, aided by an enhanced supply of fine sediment from agricultural activities on the flood plain and its effective retention, aggradation and stabilisation by colonising vegetation. Nevertheless, the restored reach has not yet fully recovered its wood-related morphological complexity. Although initial channel and habitat adjustment has occurred, sustaining the recovery in the longer term depends on continued delivery of wood by ensuring a natural supply of sufficiently large wood pieces from riparian trees both upstream and within the reach. This should lead to a continued trajectory of sediment retention and sorting, vegetation colonisation, and channel adjustment so that the channel is attuned to fluvial processes and wood supply and presents a complex assemblage of landforms and habitats.

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Table 1. Characteristics recorded for all wood jams.

Variable	Description
Number of large wood pieces in jam	Total number of large wood pieces in the jam.
Wood piece length	Average length of large wood pieces within the jam (m).
Wood piece diameter	Average mid-stem diameter of large wood pieces within the jam (m).
Jam length	Distance from the upstream to downstream edges of the wood jam measured parallel to the river channel axis (m).
Jam width	Width of the jam measured perpendicular to the river channel axis (m).
Jam depth	Maximum depth of the wood jam measured vertically from the river bed (m).
Jam volume	The volume of the smallest rectangular box (including air) into which a wood jam would fit (m^3). Following Gurnell *et al.* (2000), the wood+air volumes were adjusted to produce estimates of wood volume by multiplying the jam volume by 0.2.
Jam area	The smallest rectangular area of the ground surface into which a wood jam fits (m^2).

Table 2. Statistically significant differences ($p<0.05$) in sediment characteristics and propagule abundance of samples obtained from five patch types in May 2012 for each of the two wood reintroduction periods (R1, R2), identified using Mann Whitney (a) and Kruskal-Wallis (b and c) tests with multiple pairwise comparisons performed using Dunn's procedure with Bonferroni correction.

a - Comparison of wood reintroduction periods (R1 and R2)

	Significant differences between wood reintroduction periods						
Patches	%Organic matter	D_{50}	%Gravel	%Sand	%Silt	%Clay	Propagule abundance
All samples	n.s.	n.s.	R2 > R1	n.s.	n.s.	n.s.	n.s.
EB	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	R1 > R2
JM	n.s.	R1 > R2	n.s.	R2 > R1	R1 > R2	R1 > R2	n.s.
BK	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
JB	n.s.	R1 > R2	R2 > R1	R2 > R1	R1 > R2	R1 > R2	n.s.
FP	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

b - Comparison of patches for each wood reintroduction period (R1 and R2)

Sediment and propagule characteristics	Significant differences among patch types	
	R1 samples	R2 samples
%Organic matter	FP > EB	FP, JM > EB
D_{50}	JM > EB	JM, BK > EB
%Gravel	EB > JM	n.s.
%Sand	EB > JB, JM	EB > JB, FP, JM, BK
%Silt	JM, JB > EB	JM, BK, JB > EB
%Clay	JM, FP > EB	FP, JM, BK > EB
Propagule abundance	n.s.	FP > BK, EB

c - Comparison of patches along reach

Sediment and propagule characteristics	Significant differences among patch types
%Organic matter	FP > EB
D_{50}	JM, JB, FP, BK > EB
%Gravel	EB > JM
%Sand	EB > BK, FP, JB, JM
%Silt	JM, JB, FP, BK > EB
%Clay	JM, FP, JB, BK > EB
Propagule abundance	FP, JB > BK, EB

Table 3. Eigenvalues, percent variance explained and sediment and propagule characteristic loadings on the first two principal components (PC1, PC2) of a Principal Components Analysis (PCA) performed on the sediment and propagule characteristics of all bulk sediment sampled in May 2012 from five patch types for two wood reintroduction periods (R1, R2).

	PC1	PC2
Eigenvalue	4.102	0.979
Variance explained (%)	68.375	16.318
Cumulative variance (%)	68.375	84.692
Loadings		
%Organic matter	0.848	0.251
D_{50}*	0.974	-0.155
%Gravel	-0.680	0.202
%Sand	-0.937	0.127
%Silt+%Clay	0.982	-0.134
Propagule abundance	0.360	0.904

a - All samples (comparison of scores of R1 and R2 samples)

	Significantly different subgroups (Mann Whitney tests (MW) $p<0.05$, n.s. if no significant differences)
PC1	n.s.
PC2	n.s.

b - Comparison of scores of R1 and R2 samples for each patch type

	Significant differences between wood reintroduction periods on PCs (MW $p<0.05$)	
Patches	PC1	PC2
EB	n.s.	n.s.
JM	R1 > R2	n.s.
JB	R1 > R2	n.s.
BK	n.s.	n.s.
FP	n.s.	n.s.

c - Comparison of patches for each wood reintroduction period (R1 and R2)

	Significant differences among patch types for each wood reintroduction period (Kruskal-Wallis tests (KW) $p<0.05$)	
	R1 samples	R2 samples
PC1	JM, JB, FP > EB	FP, JM, BK, JB > EB
PC2	n.s.	FP > EB

d - Comparison of scores of all samples from the different patch types

	Significant differences among patch types (KW p<0.05)
PC1	JM, FP, JB, BK > EB
PC2	FP > BK

* because D50 is expressed in phi units, larger values denote finer sediments

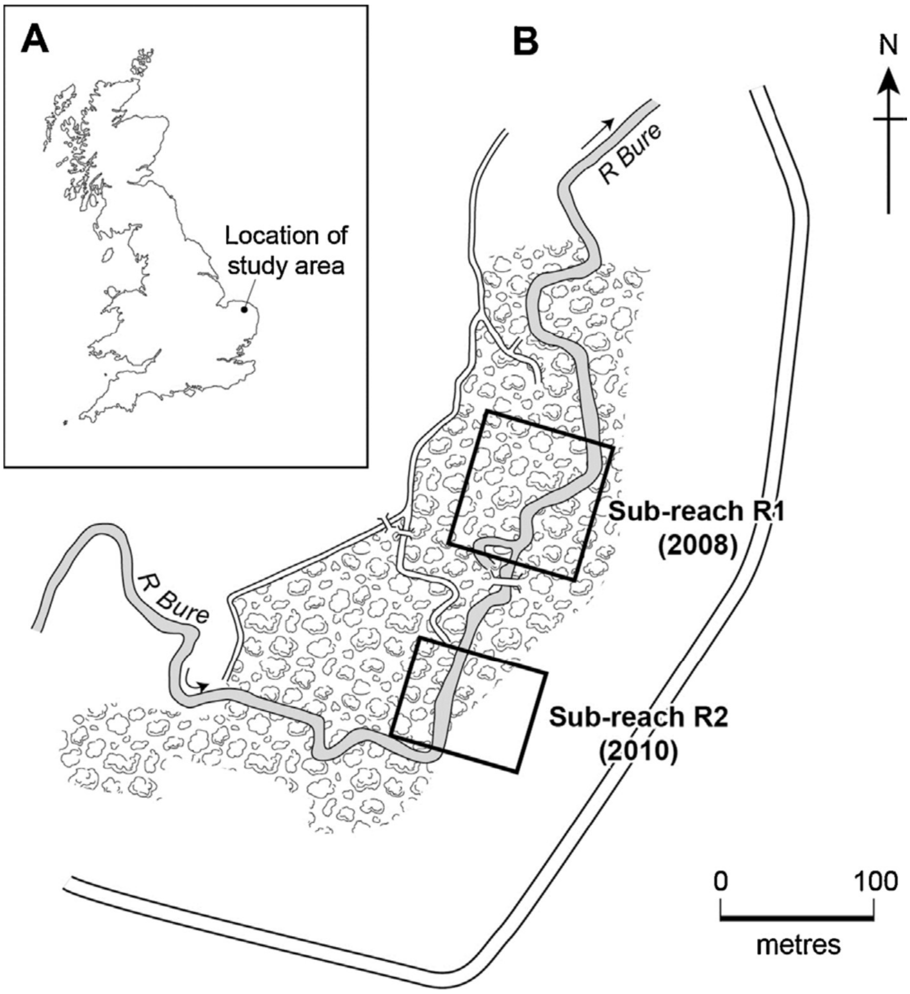

Figure 1. (A) Location of the River Bure in Eastern England; (B) the Blickling Hall estate near Aylsham showing the study reach, which includes sub-reaches affected by reintroduction of wood in autumn 2008 (sub-reach R1) and autumn 2010 (sub-reach R2) (Source: Modified from RRC, 2013).

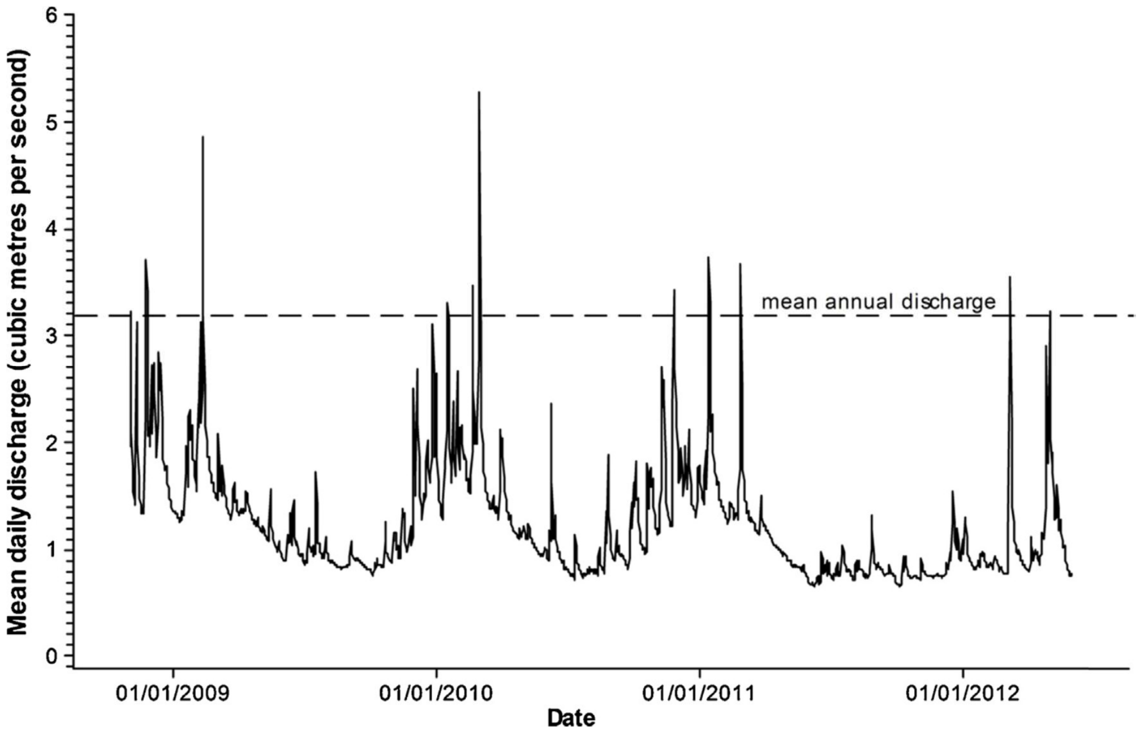

Fig. 2. Discharge time series for the River Bure at Ingworth (1 November 2008 to 31 May 2012), showing higher discharge events above the mean annual discharge thatscoured and deposited sediment along the study reach.

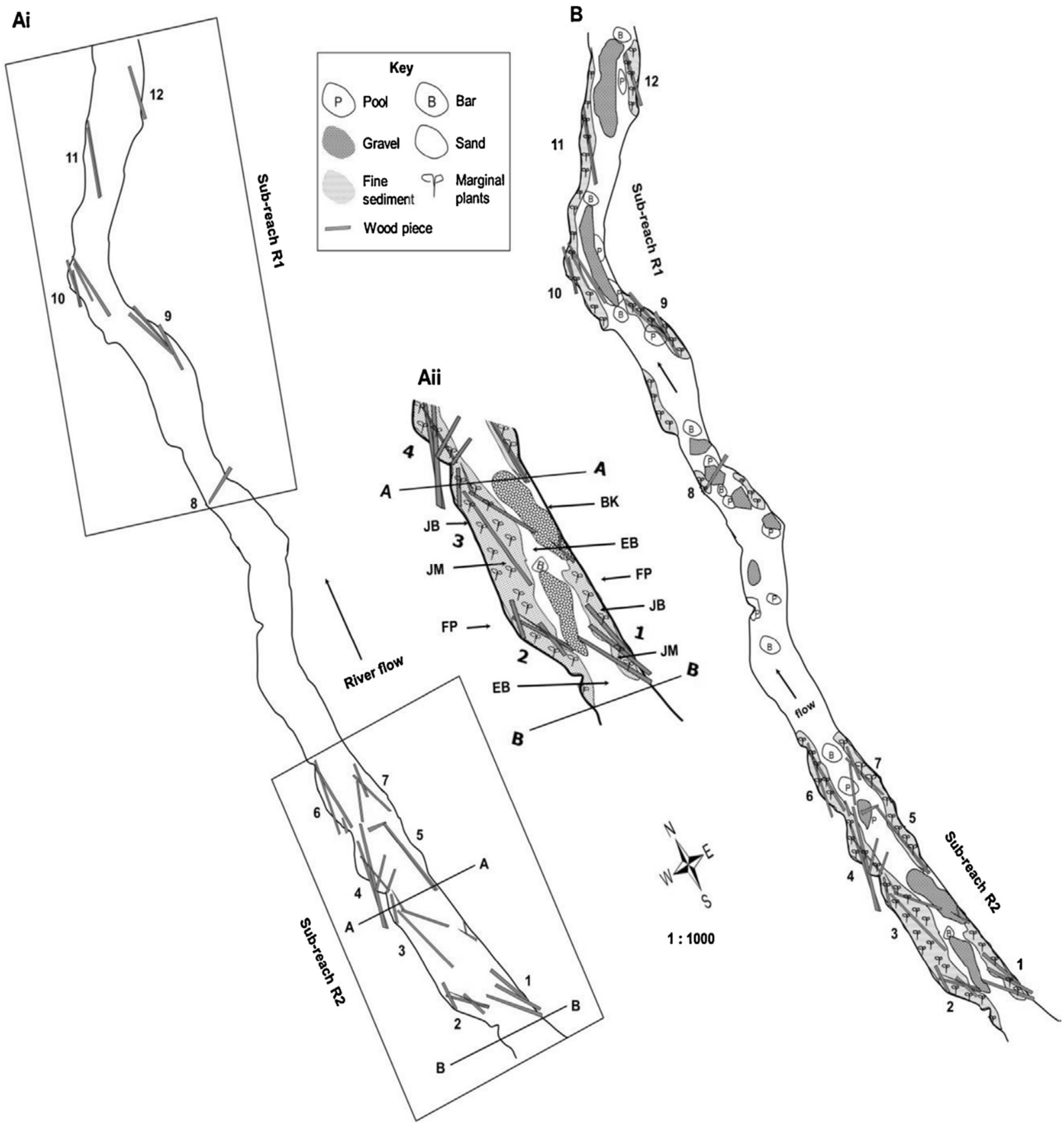

Figure 3. (Ai) The study reach (located in Figure 1B), showing the location of the large wood pieces / jams from upstream (top left) to downstream (bottom right). (Note that the wood was reintroduced into sub-reach R1 in autumn 2008 and into sub-reach R2 in autumn 2010); (Aii) Schematic representation of the typical patterning of sampled habitat patch types within the study reach. The sampled patch types were exposed river bed (EB), jam (JM), jam bank (JB), bank (BK) and floodplain (FP); (B) Geomorphological sketch map of the study reach, indicating substrate types, mesohabitats, wood pieces and jams and areas colonised by plants.

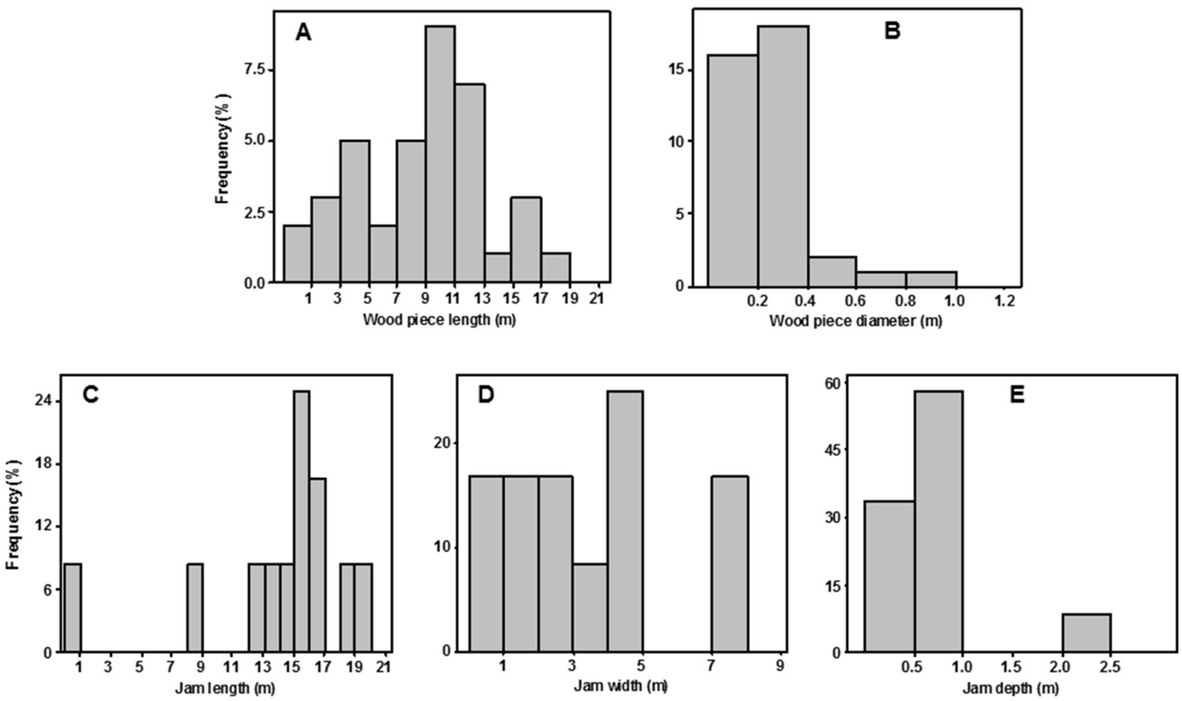

Figure 4. Percentage frequency distributions of the (A) length (m) and (B) diameter (m) of large wood pieces found within wood jams; wood jam (C) length (m), (D) width (m) and (E) depth (m).

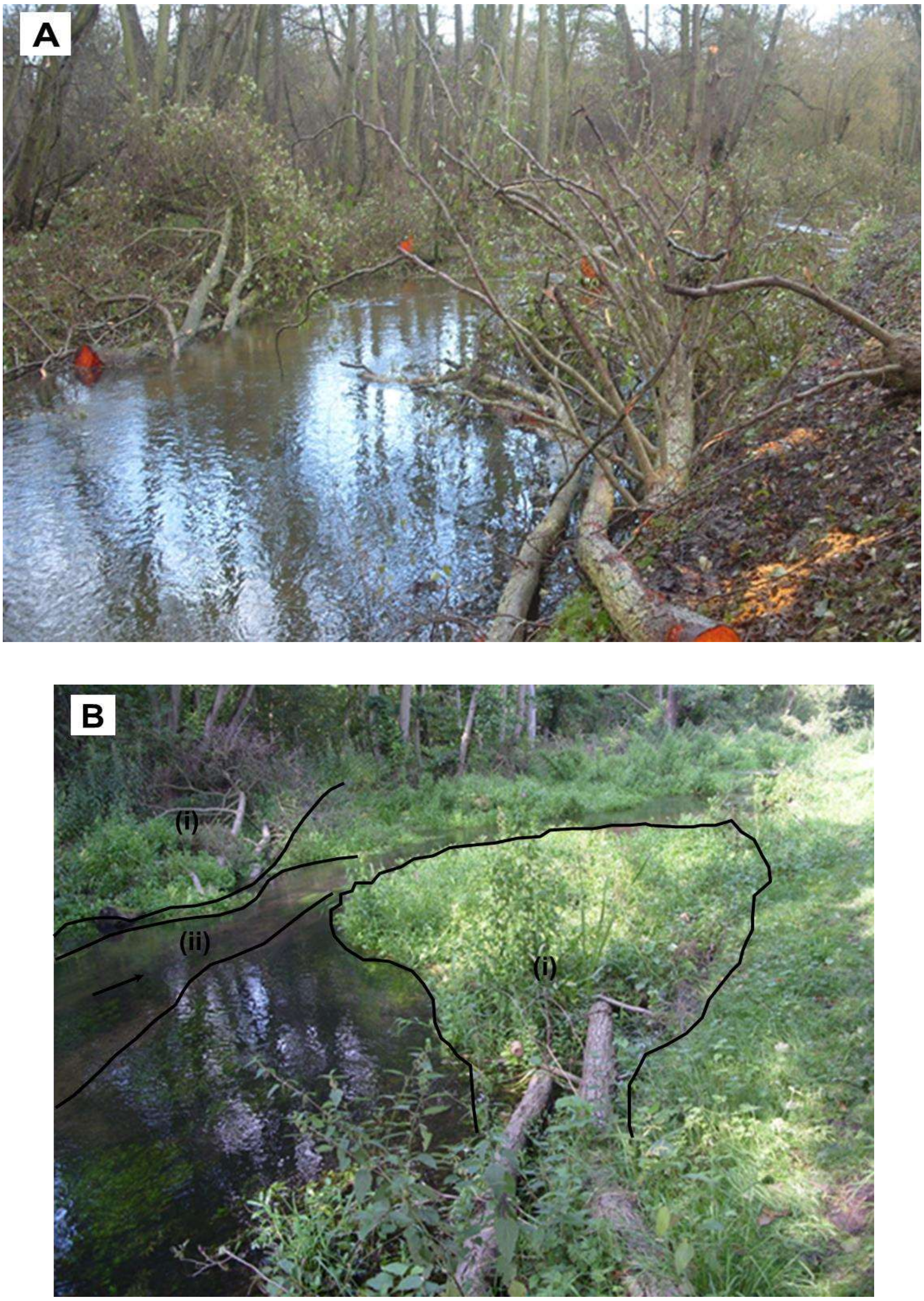

Figure 5. Fixed-point photographs of part of the study reach: (A) the introduced wood (09/11/2010) and (B) alterations in channel morphology and vegetation colonisation at the same location as A. (10/7/2012). The photograph indicates (i) vegetation within and around wood jam adjacent the floodplain, and (ii) exposed gravel bed in area of flow concentration between wood jams and associated vegetation.

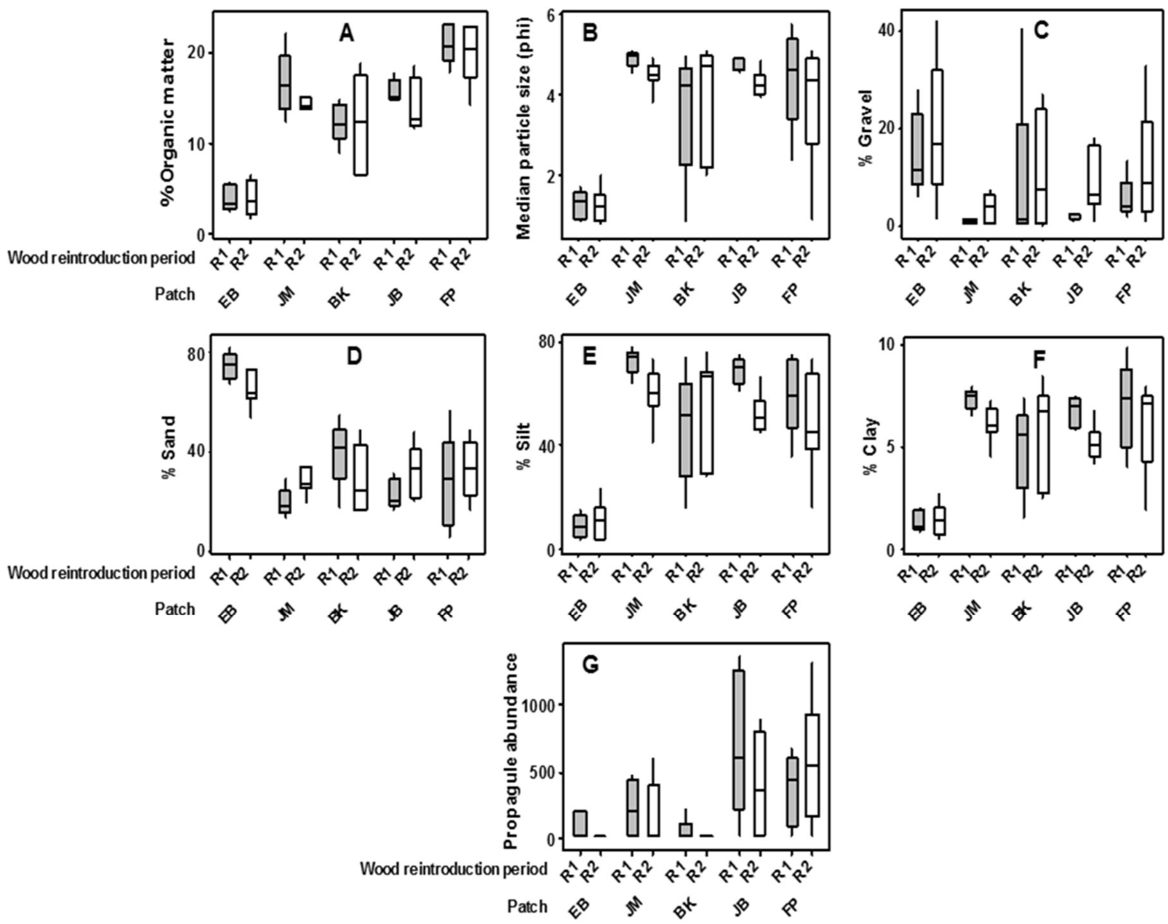

Figure 6. Box-whisker plots illustrating contrasts in sediment properties including %Organic matter (A), median particle size (phi units) (B), %Gravel (C), %Sand (D), %Silt (E) and %Clay (F) and the propagule abundance (viable propagules per square metre) (G) of samples from exposed river bed (EB), jam (JM), bank (BK), jam bank (JB) and floodplain (FP) patches in the two sub-reaches (R1 and R2). The patches are ordered along the x-axis from channel bed to floodplain, and thus show a continuum of decreasing hydrological connectivity. Boxes for sub-reaches R1 and R2 are shaded and unshaded respectively.

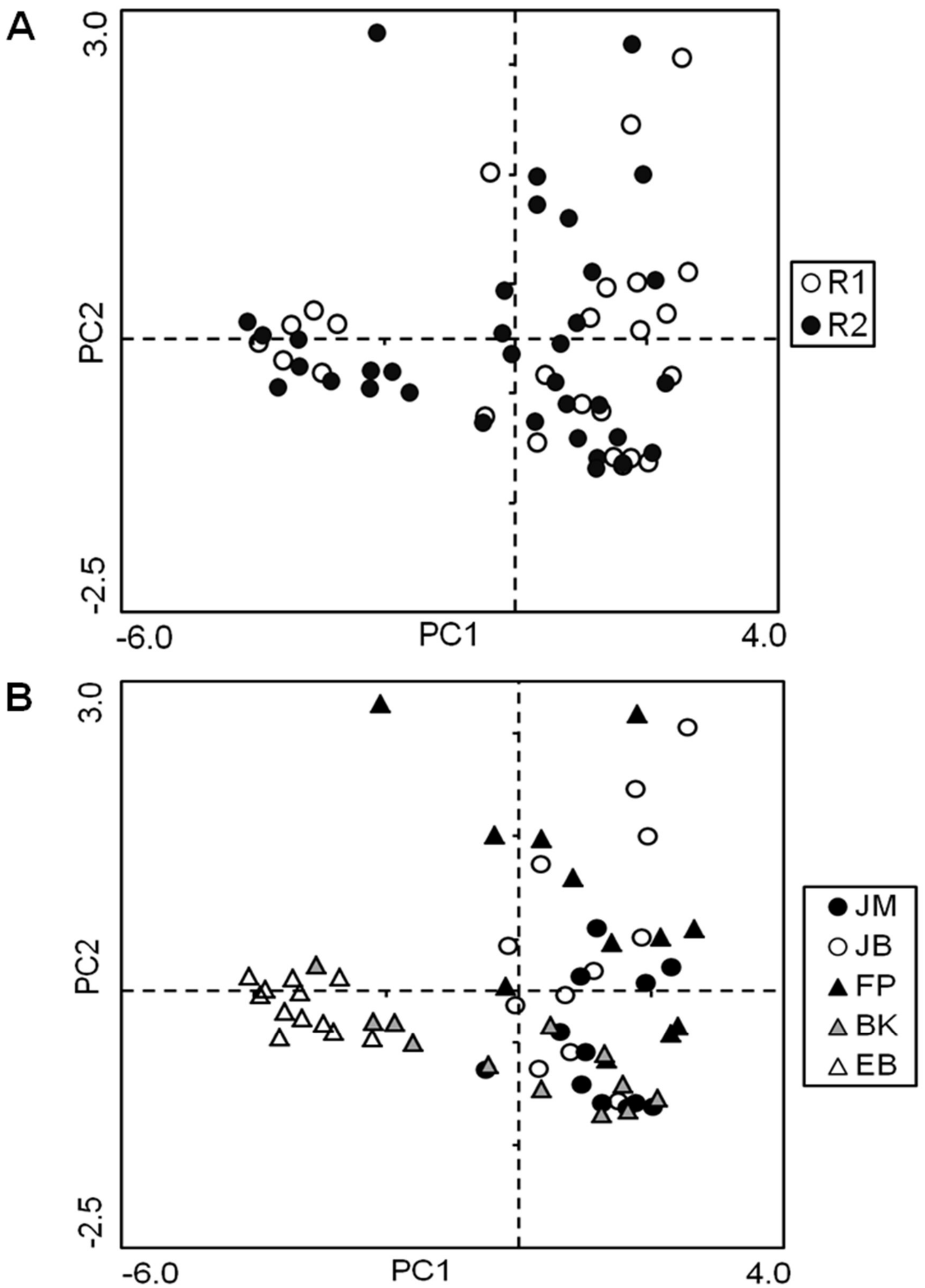

Figure 7. Scatter plot illustrating sample scores on PC1 and PC2 of the PCA described in Table 3. Samples are coded by: (A) sub-reaches with different dates of wood introduction (R1, R2); (B) patch types (EB, JM, BK, JB, FP), with circles for wood-related patches (JM, JB) and triangles for other patches (FP, BK, EB).